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Centrality dependence of freeze-out parameters from the beam energy scan at STAR

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Abstract

The STAR experiment at RHIC has a unique capability of measuring identified hadrons over a wide range of pseudorapidity (η), transverse momentum (p_T), and azimuthal angle (ϕ) acceptance. The data collected ($\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV) in its beam energy scan (BES) program provide a chance to investigate the final hadronic state freeze-out conditions of ultrarelativistic Au+Au collisions. The particle ratios are used to compare to a statistical model calculation using both grand canonical and strangeness canonical ensembles to extract the chemical freeze-out parameters. The p_T distributions are fitted to calculations using a blast-wave model to obtain the kinetic freeze-out parameters. We discuss the centrality dependence of the extracted chemical and kinetic freeze-out parameters at these lower energies.

1. Introduction

One of the early goals of heavy-ion collisions at Relativistic Heavy Ion Collider (RHIC) was to establish the existence of a new state of matter, the quark-gluon plasma (QGP) [1]. According to lattice quantum chromodynamics calculations (QCD), the transition to QGP occurs when a sufficiently high temperature and high energy density ($\approx$ 1 GeV/fm^3) is reached. The partonic system is transformed into hadronic matter as the system cools to lower temperatures. The phase diagram of QCD is in general characterized by two quantities, the temperature (T) and the baryon chemical potential (μ_B) or the (net) baryon density (n_B), and it contains information about the phase boundary that separates the QGP and hadronic phases [2]. Lattice QCD finds a rapid, but smooth crossover transition from hadron gas to QGP at vanishing baryon chemical potential and large temperature T, while various models predict a strong, first-order phase transition at large μ_B. If this is the case, then there should be a critical point at intermediate values in the (T, μ_B) plane where the transition changes from a smooth crossover to a first order [3]. The BES program at RHIC has been carried out using several center-of-mass energies of colliding nuclei to explore the above aspects of this QCD phase diagram. The constituents of the hot and dense medium produced during a heavy-ion collision interact with each other by inelastic and elastic collisions, and through these interactions, the medium evolves into a state of free particles. This process of hadron decoupling is called freeze-out. Two kinds of freeze-out are found: chemical freeze-out (T$_{ch}$) when inelastic collisions cease and the particle yields become fixed;

[1]A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

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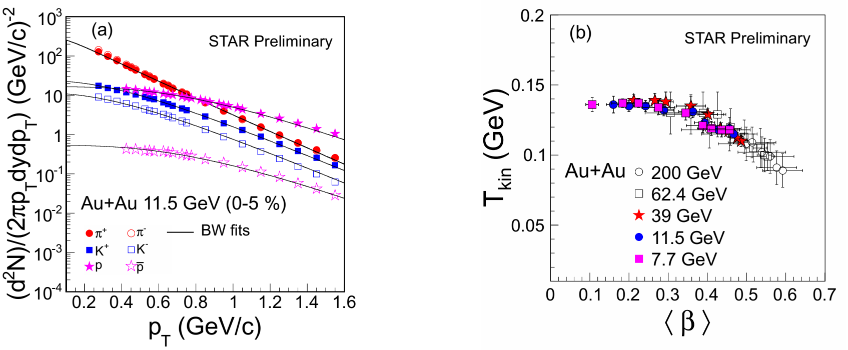

Figure 1: (a) Simultaneous blast-wave fit of charged pion, kaon and proton for 0–5% centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 11.5 GeV. (b) Variation of T$_{kin}$ with $\langle\beta\rangle$ for different centralities at $\sqrt{s_{NN}}$ = 7.7, 11.5, 39, 62.4, and 200 GeV. The 62.4 and 200 GeV results are taken from Ref. [4]. The errors shown here are the statistical and systematic errors added in quadrature.

thermal (kinetic) freeze-out (T$_{kin}$) when elastic collisions cease and particle transverse momenta (p_T) spectra are fixed.

We present a study of the centrality dependence of hadronic freeze-out parameters in Au+Au collisions at mid-rapidity for $\sqrt{s_{NN}}$ = 7.7, 11.5, and 39 GeV measured by the STAR experiment. To extract chemical freeze-out parameters we use a statistical thermal model (THERMUS) [5] where we fit experimental particle ratios using a grand canonical ensemble (GCE) approach with the inclusion of a strangeness saturation factor (γ_S) and also with strangeness canonical ensemble (SCE) where strangeness quantum number is conserved exactly. In this study we have used mid-rapidity particle ratios that include the pions (π^+, π^-), kaons (K^+, K^-), protons (p, $\bar{p}$), K^0_S, lambdas (Λ, $\bar{\Lambda}$) and cascades (Ξ^-, $\bar{\Xi}^+$) [6, 7]. The chemical freeze-out parameters extracted are T$_{ch}$, μ_B, μ_S and γ_S. The kinetic freeze-out parameters are determined from the blast-wave model (BW) [8] fits to the p_T spectra of π, K and p [6]. The main kinetic freeze-out parameters extracted are T$_{kin}$ and average flow velocity ($\langle\beta\rangle$).

2. Results

2.1. Kinetic freeze-out

At kinetic freeze-out, elastic collisions among the particles stop and the spectral shape of the particles are fixed. Kinetic freeze-out parameters are obtained using blast-wave model by doing the simultaneous fits of π, K, and p transverse momentum spectra. The BW model describes the spectral shapes assuming a locally thermalized source with a common transverse flow velocity field. It has been successfully used to describe p_T spectra with three parameters - T$_{kin}$, $\langle\beta\rangle$, and the exponent in the flow velocity profile n at 62.4 and 200 GeV [4, 9]. Figure 1(a) shows the simultaneous blast-wave fit of π, K, p and the corresponding antiparticles for 0–5% centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 11.5 GeV. The variation of T$_{kin}$ as a function of $\langle\beta\rangle$ at $\sqrt{s_{NN}}$ = 7.7, 11.5, 39, 62.4 and 200 GeV is shown in Fig. 1(b). The 62.4 and 200 GeV results are taken from Ref. [4]. The T$_{kin}$ decreases from peripheral to central collisions. It also decreases with increasing collision energy. The $\langle\beta\rangle$ increases with increase of energy as well as collision

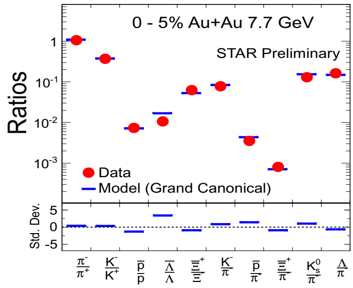

Figure 2: Statistical thermal model [5] fits to experimental mid-rapidity particle ratios for 0–5% centrality in Au+Au at $\sqrt{s_{NN}}$ = 7.7 GeV.

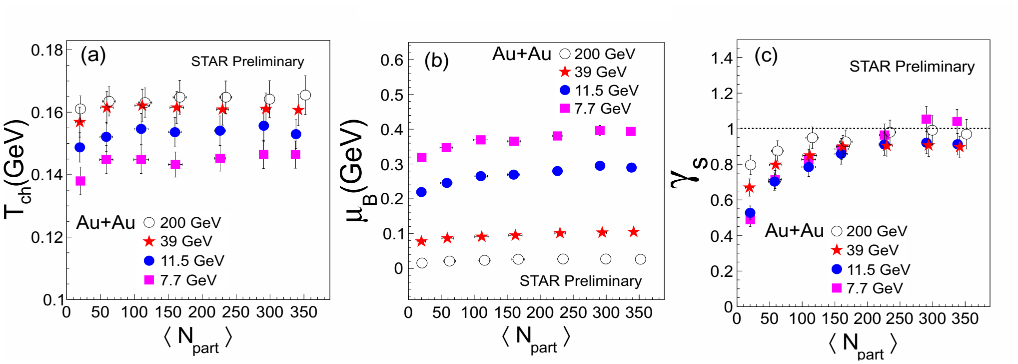

Figure 3: Results from a statistical thermal model fit [5] for Au+Au at $\sqrt{s_{NN}}$ = 7.7, 11.5, and 39 GeV. Chemical freeze-out temperature, baryon chemical potential, and strangeness saturation factor are shown as a function of N_{part}. The 200 GeV results are taken from Ref. [10].

centrality. A higher value of T_{kin} corresponds to lower value of $\langle\beta\rangle$ and vice-versa. The errors shown are the quadratic sum of statistical and systematic errors.

2.2. Chemical freeze-out

At chemical freeze-out, inelastic collisions among the particles stop and hadron yields are fixed. A statistical thermal model (THERMUS) was used to fit mid-rapidity particle ratios including yields of π, K, p, K^0_S, Λ and Ξ measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, and 39 GeV. Although the particle ratios are obtained at $y = 0$, the measurements of yields for π, K, p are for $|y| < 0.1$ and those for K^0_S, Λ , Ξ are for $|y| < 0.5$. The errors on particle ratios including yields of π, K, p, K^0_S, Λ, and Ξ, are the quadratic sum of statistical and systematic uncertainties. Pion yields have been corrected for feed-down from K^0_S weak decays. Proton yields have not been corrected for feed-down contributions. The Λ yields have been corrected for the feed-down contributions from Ξ and Ξ^0 weak decays [7]. In the framework of this model, the particle yield ratios can be described by a set of parameters such as T_{ch}, μ_B, μ_S and γ_S. The errors on freeze-out parameters are obtained from THERMUS model. Considering grand canonical formulation of this model we have studied the centrality and energy dependence of the freeze-out parameters.

Figure 2 shows the statistical model fits to experimental particle ratios for 0–5% centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV. The data and model matches very well, except for

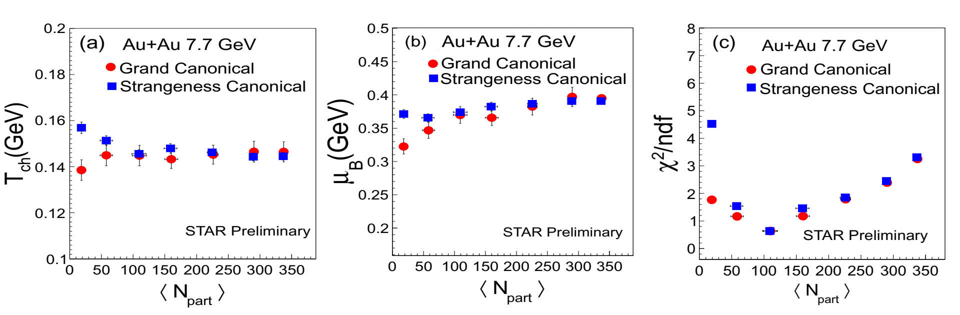

Figure 4: Results from a statistical thermal model fit [5] for Au+Au at $\sqrt{s_{NN}}$ = 7.7 GeV in GCE and SCE. Chemical freeze-out temperature, baryon chemical potential and χ^2 per degree of freedom are shown as a function of N_{part}.

$\bar{\Lambda}/\Lambda$. Figure 3 (a) shows the T$_{ch}$ increases with increase of collision energy. Figure 3(b) shows μ_B decreases with increasing collision energy. From peripheral to central collisions, μ_B increases at lower energies. We observe a centrality dependence of chemical freeze-out curve (T$_{ch}$ vs. μ_B) at BES energies which was not observed at higher energies like Au+Au 200 GeV [10]. Figure 3 (c) shows that the γ_S increases from peripheral to central collisions for all energies.

In contrast to GCE where all quantum numbers are conserved on an average, THERMUS model also allows for a strangeness canonical ensemble where only the strangeness quantum number is required to be conserved exactly where as baryon and charge quantum numbers are conserved on an average. Figure 4 (a) and (b) indicate that in peripheral collisions, T$_{ch}$ and μ_B follow a different behavior in GCE and SCE at $\sqrt{s_{NN}}$ = 7.7 GeV. We observe a higher χ^2/ndf in SCE in comparison to GCE at peripheral collisions. Further systematic investigations are ongoing towards a more quantitative analysis for all the BES energies.

3. Summary

The new BES measurements at $\sqrt{s_{NN}}$ = 7.7, 11.5, and 39 GeV at RHIC extend the μ_B range from 20 to 400 MeV in the QCD phase diagram. Kinetic freeze-out parameters are obtained using the measured particle spectra and a BW model. For all the beam energies studied, the central collisions are characterized by a lower T$_{kin}$ and larger $\langle\beta\rangle$ while the peripheral collisions are found to have a higher T$_{kin}$ and smaller $\langle\beta\rangle$. Chemical freeze-out parameters are obtained using the measured particle ratios and a THERMUS model. We have observed a centrality dependence of the chemical freeze-out parameters at the lower energies. We have observed different behavior of chemical freeze-out parameters (T$_{ch}$, μ_B) for peripheral collisions in GCE and SCE.

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